Developing an Economical Hyperspectral Imaging System Using Sequential Gas Discharge Illumination for Large Targets

Douglas C. Youvan
doug@youvan.com
March 19, 2024

Hyperspectral imaging (HSI) is a transformative technology that captures the spectrum for each pixel in an image, offering unparalleled insights into the material properties of a target. Traditionally, HSI systems have been cost-prohibitive and complex, limiting their accessibility and use in analyzing large targets like artworks, documents, and historical artifacts. This paper introduces an economical and simplified HSI system that leverages sequential gas discharge illumination and a standard CMOS camera, making hyperspectral imaging more accessible for large-scale applications. By utilizing a dual-phase calibration process, including a high-reflectivity white standard and a target with predefined dyes, this method ensures accurate spectral analysis. This innovative approach democratizes HSI, opening up new possibilities for detailed material analysis in art conservation, forensic science, and beyond. It presents a practical framework for the widespread adoption of HSI, significantly reducing the barriers to entry for researchers, educators, and industry professionals seeking to employ this powerful analytical technique.

Keywords: hyperspectral imaging, economical HSI system, sequential gas discharge illumination, CMOS camera, large-scale applications, dual-phase calibration, spectral analysis, material analysis, art conservation, forensic science, predefined dyes, standard CMOS camera, gas discharge lamps, high-reflectivity white standard, spectral deconvolution.

Abstract

This study introduces an innovative and cost-effective hyperspectral imaging system designed for analyzing large targets such as artworks and documents. Utilizing sequential illumination from gas discharge tubes across the visible spectrum, combined with a CMOS camera, this methodology simplifies the acquisition of hyperspectral data. Central to ensuring accuracy and reliability in spectral analysis is the implementation of a dual-phase calibration process: one leveraging a high-reflectivity white standard and another using a target with predefined dyes of known absorption spectra. This paper details the mathematical models for radiometric calibration and spectral deconvolution, offering a practical framework for widespread adoption in conservation, forensics, and material science.

In recent years, the demand for hyperspectral imaging has surged across various fields, notably in the conservation of historical artifacts, forensic analysis, and material science, due to its unparalleled capability to provide detailed spectral information for each pixel in an image. However, traditional hyperspectral imaging systems are often burdened by high costs, complex operational requirements, and the need for sophisticated optical components, limiting their accessibility and practicality for analyzing large-scale objects like artworks and historical documents. Addressing these challenges, this study presents a novel and economically viable hyperspectral imaging system that exploits sequential illumination from gas discharge tubes, spanning the entire visible spectrum, in conjunction with a commercially available CMOS camera. This approach markedly simplifies the process of acquiring hyperspectral data while significantly reducing the overall system cost.

A key innovation of this methodology is its dual-phase calibration process, which is crucial for achieving high accuracy and reliability in spectral analysis. The first phase utilizes a high-reflectivity white standard to perform flat fielding, ensuring uniform illumination across the imaging field and calibrating the camera's response. The second phase introduces a novel element to the calibration process—a target adorned with spots of defined dyes, each characterized by well-documented absorption spectra. This addition enables the precise deconvolution of the emission spectra

from the gas discharge lamps, allowing for the accurate reconstruction of the hyperspectral data of the illuminated target.

The mathematical foundations underpinning this methodology, particularly the models for radiometric calibration and spectral deconvolution, are delineated in detail within this paper. These models facilitate the extraction of refined spectral information from the raw images captured under varied spectral lighting conditions, paving the way for a deeper understanding of the material properties of the target objects. By offering a cost-effective, simplified, and highly accurate hyperspectral imaging solution, this study aims to democratize the use of this powerful imaging technique, making it accessible to a broader range of applications in art conservation, forensic investigation, and beyond. The proposed system not only challenges the status quo of hyperspectral imaging technology but also provides a scalable and practical framework poised for widespread adoption in fields where the detailed spectral analysis of large targets is indispensable.

Introduction

Hyperspectral imaging (HSI) stands at the forefront of modern imaging technologies, offering the unique ability to capture detailed spectral information for each pixel within an image. This capability allows for the identification and analysis of materials, chemical compositions, and other properties invisible to the naked eye, making HSI a powerful tool across a wide range of applications. From the precise monitoring of agricultural health to the intricate analysis of historical artworks, the depth of data provided by HSI facilitates advancements in fields as diverse as environmental science, medical diagnosis, food safety, and cultural heritage preservation.

Despite its vast potential, the widespread adoption of HSI technology faces significant barriers, primarily due to the high costs associated with traditional hyperspectral cameras and the complexity of the systems involved. These traditional setups often require sophisticated optical components, such as diffraction gratings or tunable filters, and extensive calibration procedures to ensure accurate spectral data acquisition. Additionally, the size and sensitivity of these systems can limit their

applicability, especially for in-situ analysis of large or delicate targets like murals, tapestries, or extensive document archives.

In response to these challenges, this study introduces an innovative approach to hyperspectral imaging that significantly reduces both cost and operational complexity. By employing sequential illumination from gas discharge tubes—each emitting light at specific, characteristic wavelengths across the visible spectrum—and capturing the resultant reflections with a standard CMOS camera, this method simplifies the acquisition of hyperspectral data. This approach not only makes HSI technology more accessible but also adapts it for large-scale applications without the need for high-end, specialized imaging equipment.

A pivotal aspect of enhancing the accuracy and reliability of this system lies in the calibration process. Unlike conventional methods that might rely solely on uniform light sources or complex optical calibrations, this methodology incorporates a dual-phase calibration process. The first phase uses a high-reflectivity white standard to achieve a uniform baseline across the imaging field. The second, more innovative phase employs a target featuring spots of defined dyes with well-known absorption spectra. This strategic inclusion allows for the precise deconvolution of the emission spectra from the gas discharge lamps, facilitating the accurate reconstruction of the target's hyperspectral image. The predefined dyes serve not only as a tool for calibration but also as a benchmark for validating the spectral accuracy of the imaging system, underscoring the critical role of advanced calibration in enhancing the fidelity of hyperspectral data.

By navigating the limitations of conventional HSI systems and proposing a low-cost, simplified alternative, this study aims to broaden the horizons of hyperspectral imaging. The use of gas discharge tubes for sequential illumination, combined with the novel calibration strategy involving predefined dyes, presents a practical and efficient solution for capturing hyperspectral information from large targets. This advancement holds the promise of unlocking new possibilities in research, conservation, and beyond, making the detailed insights offered by hyperspectral imaging more accessible to all.

Background

The development of hyperspectral imaging (HSI) represents a significant evolution in optical technologies, marking a shift from traditional photography and monochromatic imaging towards capturing a comprehensive spectral fingerprint of every pixel within a scene. This advancement allows for the detailed analysis of material properties, chemical compositions, and other characteristics that are not discernible through conventional imaging techniques. Originating from remote sensing applications designed for Earth observation from satellites, HSI technology has gradually transitioned into a myriad of other fields, including agriculture, environmental monitoring, medical imaging, and art conservation. This transition towards accessible technology has been fueled by the growing recognition of HSI's potential to provide unparalleled insights into the physical world.

Despite its promising capabilities, the adoption of conventional hyperspectral imaging systems has been hampered by significant challenges. The primary hurdle is the cost associated with these systems, which often incorporate expensive optical components like diffraction gratings, tunable filters, or acousto-optic tunable filters to achieve spectral dispersion. Additionally, the operational complexity of traditional HSI setups, requiring precise calibration and alignment, specialized knowledge for data analysis, and often cumbersome hardware, poses a barrier to its widespread application, especially in fields requiring mobility or the analysis of large, immovable objects.

The seminal work in digital imaging spectroscopy, particularly developments in the late 20th and early 21st centuries, laid the groundwork for modern HSI techniques. Innovations such as the use of Fabry-Perot interferometers for multi-spectral filtering illuminated paths towards more versatile imaging solutions. These pioneering efforts demonstrated the feasibility of extracting detailed spectral information from a scene, albeit with systems that were typically complex and costly. Notably, the research conducted at prestigious institutions, including the Massachusetts Institute of Technology (MIT), introduced digital imaging spectroscopy into the academic and research mainstream, highlighting the technique's potential for diverse applications beyond remote sensing.

The proposed methodology in this study builds upon these foundational insights but aims to significantly lower the barriers to HSI technology adoption. By simplifying the hardware requirements and leveraging sequential gas discharge illumination—a concept that draws inspiration from the emission spectra characteristic of different gases—a more economical and user-friendly approach to hyperspectral imaging is presented. This method not only addresses the financial and operational constraints associated with traditional HSI equipment but also introduces a novel calibration technique using predefined dyes with known absorption spectra. This dual-phase calibration process ensures the accuracy and reliability of the spectral data acquired, making the system suitable for a wide range of applications, from analyzing large artworks to conducting forensic document examinations.

As we continue to develop and refine hyperspectral imaging technologies, the emphasis on accessibility and practicality will likely drive further innovations in the field. The journey from high-end, specialized equipment to more user-friendly and cost-effective solutions reflects a broader trend in scientific instrumentation towards democratizing advanced analytical capabilities. This background sets the stage for the proposed methodology, which represents a significant step towards making hyperspectral imaging a common tool across various disciplines, enabling researchers and professionals alike to uncover hidden details in the world around us.

Methodology

System Design

The proposed hyperspectral imaging system is engineered to be both cost-effective and accessible, without compromising on the quality of spectral data obtained from large targets. The system's cornerstone is the strategic use of gas discharge lamps, each selected for its unique spectral emission characteristics across the visible spectrum (400 - 700 nm). These lamps are arranged sequentially around the imaging area to provide controlled, monochromatic illumination over the target, one wavelength band at a time. This setup includes gases such as neon for red, argon for blue, and others to cover the entire visible range comprehensively.

The choice of a standard CMOS camera as the imaging sensor is pivotal to the system's design for several reasons. First, CMOS technology offers a high dynamic range and sensitivity necessary for detecting subtle differences in reflected light from the target under various spectral illuminations. Second, the camera is set to grayscale mode, transforming it into an effective photon counter that measures intensity variations across the spectrum linearly, a crucial feature for spectral analysis.

Calibration Process

Phase 1: Flat Fielding with a High-Reflectivity White Standard

The first phase of calibration involves illuminating a white standard known for its high reflectivity (close to 99%) under the same sequential lighting conditions used for imaging the target. This process ensures that variations in illumination intensity across different spectral bands are accounted for, normalizing the camera's response to provide a uniform baseline for all subsequent imaging. This step is critical for correcting spatial illumination inconsistencies and sensor-specific sensitivity variations.

Phase 2: Spectral Calibration Using Predefined Dyes

The second calibration phase introduces a target embedded with spots of predefined dyes, each selected for its well-documented absorption spectrum. This target serves as a spectral reference, enabling the fine-tuning of the system's spectral response. By comparing the known absorption properties of the dyes with the captured images under each gas discharge lamp's illumination, this phase allows for the precise deconvolution of the lamp spectra, a crucial step for accurately reconstructing the hyperspectral image of the actual target.

Mathematical Modeling for Spectral Analysis

Radiometric Calibration

The mathematical model for radiometric calibration involves quantifying the camera's response to the white standard's reflectivity across the spectrum. This process is formalized through an equation that relates the intensity of light captured by the camera to the known reflectance of the white standard, adjusting for the lamp-specific emission characteristics and the

camera's intrinsic sensitivity. This calibration ensures that subsequent measurements reflect true variations in the target's reflectance rather than inconsistencies in the imaging setup.

Spectral Deconvolution with Predefined Dyes

Spectral deconvolution is performed using a mathematical formulation that leverages the known absorption spectra of the predefined dyes. This process involves solving a set of equations that model the interaction between the emitted light from each lamp and the dyes' absorption characteristics, as captured by the camera. By accurately deconvolving this interaction, the method allows for the reconstruction of the target's spectral signature from the composite images obtained under different spectral illuminations. This step is critical for extracting meaningful spectral information from the imagery, enabling detailed analysis of the target's material composition and properties.

The proposed methodology embodies a practical approach to hyperspectral imaging, addressing traditional barriers to access while laying out a clear, mathematically grounded framework for spectral data acquisition and analysis. Through this innovative system design and calibration process, the method paves the way for new applications and research opportunities in fields requiring detailed spectral insights.

Implementation

Implementing an economical hyperspectral imaging system as described requires careful consideration of both the hardware setup and the software development to ensure affordability, ease of use, and accuracy in spectral analysis. The goal is to make hyperspectral imaging accessible for applications such as art restoration, document analysis, and educational purposes, where budget constraints might otherwise limit the use of advanced imaging technologies.

Hardware Specifications

Gas Discharge Lamps:

- **Selection:** A series of gas discharge tubes, each containing a different pure gas (e.g., neon, argon, hydrogen), is selected to cover the visible spectrum range (400 - 700 nm) through their characteristic emission lines.
- **Arrangement:** The lamps are positioned around the target in a manner that ensures uniform illumination across its surface. This may involve adjustable stands and diffusers to evenly distribute the light.

CMOS Camera:

- **Camera Selection:** A low-cost CMOS camera with high sensitivity in the visible spectrum is chosen. The camera should support grayscale mode to function as a linear photon counter, capturing the intensity of reflected light without color processing.
- **Mounting and Alignment:** The camera is securely mounted on a tripod or stand, aligned perpendicular to the target to minimize distortion and ensure consistent focus across the imaging field.

Illumination Control:

- An interface or control system is developed to sequentially activate each gas discharge lamp, allowing time for the camera to capture an image under each specific spectral condition.

Software Development

Image Processing Suite:

- **Calibration Module:** This component processes images of the high-reflectivity white standard and the calibration target with predefined dyes to perform system calibration. It adjusts for illumination uniformity and compensates for the camera's spectral response.
- **Spectral Deconvolution Algorithm:** Implements mathematical models for radiometric calibration and spectral deconvolution. It uses the known absorption spectra of the dyes on the calibration target to

accurately deconvolve the lamp spectra from the images, reconstructing the target's hyperspectral signature.
- **Data Analysis and Visualization:** Tools for analyzing the hyperspectral data, including pixel-wise spectral analysis, material identification, and visualization of spectral distributions across the target.

User Interface:

- **Design Principles:** The interface is designed to be intuitive, allowing users with limited technical expertise to operate the system. It includes straightforward controls for initiating scans, selecting analysis parameters, and viewing results.
- **Functionality:** Features include step-by-step guidance for system calibration, options for selecting specific spectral regions for analysis, and tools for visualizing and comparing spectral signatures.
- **Integration:** Ensures seamless integration with the camera and illumination control system, facilitating automated image capture and processing workflows.

Implementation Considerations

Cost-Effectiveness:

- Components are selected based on a balance of affordability and functionality. Open-source software and readily available hardware components are preferred to minimize costs.

Replicability:

- Detailed documentation is provided, including setup instructions, software configuration guides, and troubleshooting tips, ensuring that the system can be replicated by others.

Adaptability:

- The system is designed to be modular, allowing for future upgrades, such as the addition of more gas discharge lamps for extended spectral coverage or integration with different types of cameras.

By adhering to these specifications and considerations, the implementation of the proposed hyperspectral imaging system aims to provide a practical and accessible tool for spectral analysis. This approach democratizes advanced imaging capabilities, offering new opportunities for research, education, and preservation efforts across a range of disciplines.

Mathematical Modeling for Spectral Analysis

Radiometric Calibration

Radiometric calibration is an essential step in hyperspectral imaging to ensure that the pixel values accurately reflect the light intensity emitted or reflected by the target. This calibration compensates for variations in illumination intensity, camera sensitivity, and lens vignetting, which can otherwise distort the spectral information. The process involves capturing images of a uniform, high-reflectivity white standard under the same illumination conditions used for the target. This white standard, ideally reflecting close to 100% of the incident light across the visible spectrum, serves as a baseline for normalization.

The mathematical approach for radiometric calibration can be expressed as follows:

Let $I_{ws}(\lambda, x, y)$ be the intensity recorded by the camera at pixel location (x, y) and wavelength λ when imaging the white standard. Similarly, let $I_{raw}(\lambda, x, y)$ be the raw intensity recorded from the target under the same conditions. The calibrated intensity $I_{cal}(\lambda, x, y)$ for each pixel in the target image can then be derived using:

$$I_{cal}(\lambda, x, y) = \frac{I_{raw}(\lambda,x,y)}{I_{ws}(\lambda,x,y)} \times R_{ws}(\lambda)$$

where $R_{ws}(\lambda)$ represents the known reflectance of the white standard at wavelength λ. This formula adjusts the raw pixel values to account for system-wide variations, yielding calibrated intensities that more accurately represent the target's reflective properties.

Spectral Deconvolution Using Predefined Dyes

Spectral deconvolution is the process of extracting specific spectral information from the collected hyperspectral data, which is particularly challenging when dealing with broadband illumination sources like gas discharge lamps. The introduction of a calibration target adorned with spots of predefined dyes, each with a well-documented absorption spectrum, allows for the precise deconvolution of the lamp spectra.

The mathematical formulation for spectral deconvolution involves comparing the observed spectra from the target, $S_{obs}(\lambda, x, y)$, against the known spectra of the predefined dyes, $S_{dye}(\lambda)$. The goal is to find a set of coefficients $C_{dye}(x, y)$ that best fit the observed data to the model generated by linear combinations of the dye spectra. This can be expressed as an optimization problem:

$$S_{obs}(\lambda, x, y) \approx \sum_{dye} C_{dye}(x, y) \cdot S_{dye}(\lambda)$$

where the sum is over all dyes used in the calibration target. The coefficients $C_{dye}(x, y)$ represent the contribution of each dye's spectrum to the observed pixel value and can be solved for using least squares or another optimization technique.

This deconvolution process not only refines the calibration of the hyperspectral imaging system but also enables the accurate extraction of the target's spectral characteristics. By leveraging the known absorption spectra of the dyes, it's possible to accurately recover the spectral information from the illuminated targets, despite the broad and overlapping emission spectra of the gas discharge lamps. This approach enhances the system's ability to discern subtle spectral differences and patterns within the target, opening new avenues for material identification and analysis in a wide range of applications.

Discussion

The development and implementation of a cost-effective hyperspectral imaging system, as described in this paper, signify a pivotal advancement

towards democratizing hyperspectral imaging technology. By leveraging the unique spectral characteristics of gas discharge lamps for sequential illumination and employing a standard CMOS camera, this methodology presents an accessible solution for acquiring hyperspectral data across large-scale applications. The dual-phase calibration process, incorporating both a high-reflectivity white standard and a target with predefined dyes of known absorption spectra, ensures the accuracy and reliability of the spectral analysis. This innovative approach not only addresses the financial and technical barriers associated with traditional hyperspectral imaging systems but also opens up new possibilities for comprehensive material analysis in fields as diverse as art conservation, forensic science, and material science.

The implications of this cost-effective approach extend far beyond the initial cost savings on hardware. By simplifying the operational complexities typically associated with hyperspectral imaging, this methodology encourages broader adoption and exploration within the scientific community and industry. Fields requiring detailed material analysis stand to benefit significantly, as this technology enables the non-invasive examination of artworks, historical documents, and other valuable artifacts. Furthermore, the ability to conduct precise counterfeit detection offers invaluable tools for security and authentication processes.

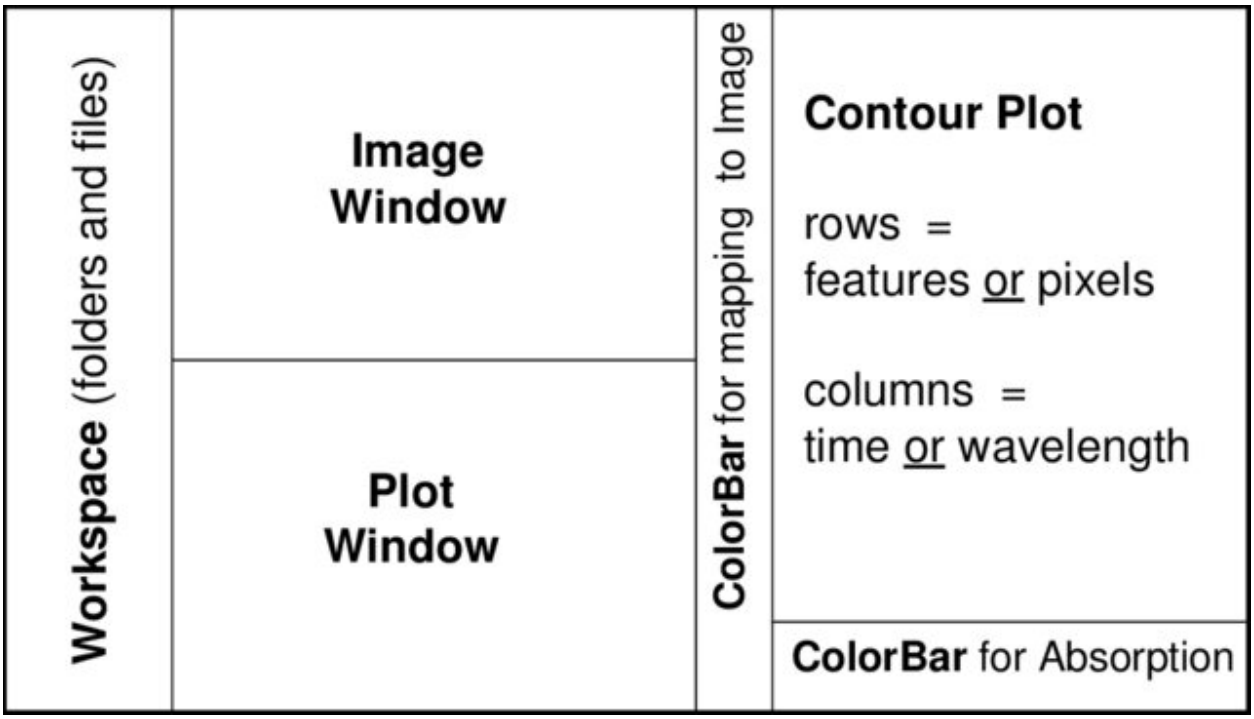
Looking forward, there are several avenues for enhancing the system's capabilities and further reducing operational complexities. One area of focus could involve exploring additional gas discharge lamps or LED sources that cover a wider range of the electromagnetic spectrum, potentially extending the applicability of this technique beyond the visible range. The development of more intuitive and powerful software tools for image processing and spectral data analysis could also significantly impact the system's usability and analytical precision. Incorporating machine learning algorithms for automatic spectral signature identification and classification may streamline the analysis process, making it more efficient and user-friendly.

Moreover, ongoing advancements in sensor technology and imaging techniques may provide opportunities to improve the system's sensitivity and resolution. Such enhancements would allow for even finer distinctions in material properties and composition, further expanding the potential applications of hyperspectral imaging.

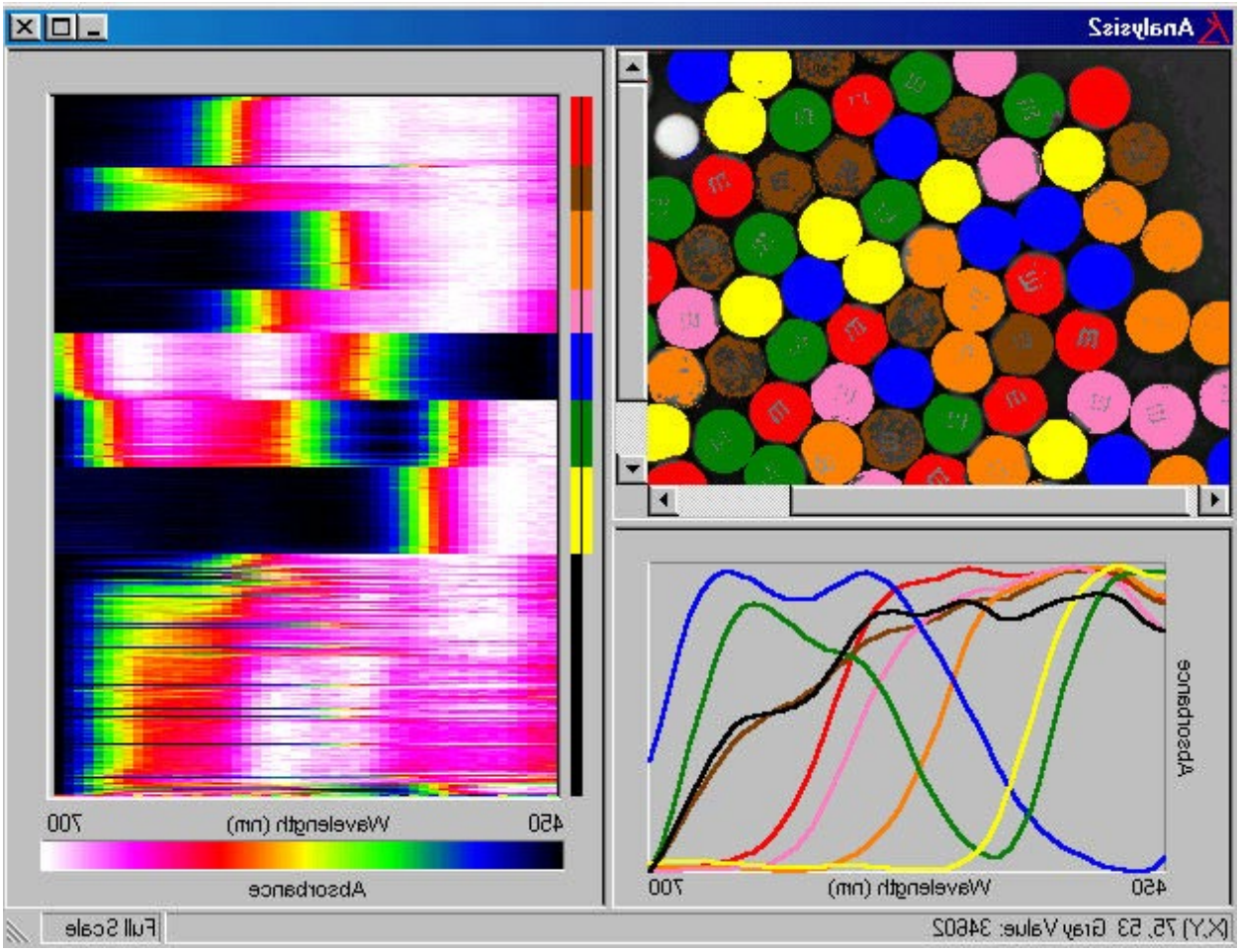
In conclusion, the proposed methodology represents a significant step towards making hyperspectral imaging a practical and accessible tool for a wide array of research and industrial applications. As we continue to refine and develop this technology, its potential to reveal hidden details and unlock new insights into the material world will undoubtedly lead to innovative discoveries and applications across multiple disciplines.

Graphical user interface for single-pixel spectroscopy

Digital imaging spectroscopy (DIS) combines image processing and optical spectroscopy such that each picture element (pixel) or group of pixels in a two dimensional scene also includes additional dimension(s) of spectral and/or temporal information. Imaging spectrophotometers developed at KAIROS are literally equivalent to hundreds of thousands of conventional spectrophotometers running in parallel, i.e., each pixel is functionally equivalent to a single 'instrument'. Because of the amount of data acquired by this massively parallel technique − often in the gigabyte range for a single experiment − it was necessary to develop a new generation of graphical tools for data analysis and display. A unifying theme in our software development is the use of multispectral color contour plots to concisely represent data from a variety of different imaging experiments. Typically, the rows of a color contour plot represent encoded information for individual pixels. The columns of a contour plot represent the values of the variable that are being measured: absorbance, reflectance, fluorescence, FRET, or time course (kinetic) data. Contour plots are very powerful for classifying pixels with similar properties; therefore, these areas within the image can be 'back-painted' with a specific pseudocolor. Numerous sorting algorithms can be applied to the contour plot to map spectral and kinetic information back onto the spatial representation in run-time. Guided by the heuristics of parameters input by the user, the application of sorting algorithms to contour plots results in a near optimal interface between machine and human intelligence for the visualization of hyperspectral and/or hypertemporal images. In addition to a general introduction to the DIS graphical user interface, we demonstrate this new technology on H&E stained tissue.



Graphical user interface for digital imaging spectroscopy utilizes coordinately controlled windows that are interactive in run-time. Note that two separate color bars are used to concisely encode information: (1) The horizontal bar under the contour plot provides a color-coded scale for the variable plotted within the contour plot. (2) The vertical bar (optional) to the left of the contour plot indicates rows that have been grouped and backcolored onto the image.



Screen dump of the GUI demonstrating reflectance imaging spectroscopy and single pixel analyses of M&M's candies.

References

nature biotechnology

Research Paper | Published: 01 August 1988

Applications of Imaging Spectroscopy in Molecular Biology: I. Screening Photosynthetic Bacteria

Mary M. Yang & Douglas C. Youvan

Bio/Technology **6**, 939–942 (1988) | Cite this article

82 Accesses | **18** Citations | **3** Altmetric | Metrics

Abstract

We have developed an imaging spectrophotometer that combines the spatial-resolving properties of a video camera with the wavelength-resolving properties of a spectrophotometer. This instrument is especially useful for screening photosynthetic bacteria, since hundreds of colonies may be analyzed simultaneously through the chromophoric properties of the photosynthetic pigments. Enhanced fluorescence mutants (possessing defective photosynthetic reaction centers) can be imaged in realtime using a silicon target camera. Mutant screening is further facilitated through imaging spectroscopy, wherein images obtained at specific wavelengths are mixed to generate pseudo images of the colonies. Digital image processing techniques can then be used to highlight distinguishing spectroscopic features of the colonies. Future applications of imaging spectroscopy to other areas of molecular biology are discussed.

Methods in Enzymology
Volume 246, 1995, Pages 732-748, IN1-IN4

[29] Digital imaging spectroscopy for massively parallel screening of mutants

Douglas C. Youvan, Ellen Goldman, Simon Delagrave, Mary M. Yang

Show more

+ Add to Mendeley Share Cite

https://doi.org/10.1016/0076-6879(95)46031-4

Get rights and content

Publisher Summary

The applications of Digital Imaging Spectroscopy (DIS) have illustrated the differentiation of mutant colonies based either on ground state absorption spectra or fluorescence emission spectra. Clearly, these first experiments on chlorophyll-based systems are generalizable to other biological targets producing chromogenic natural substances. Extrinsic dye indicators might also be coupled with DIS analysis as microbiologists continue to develop chromogenic assays. Some of these assays are based on growth rates (rather than color) and are therefore amenable to simple analysis utilizing differences in light scattering. DIS analyses could also be used to eliminate some of the artifacts encountered in conventional microtiter tray readers that are sensitive to variability in sample color or scattering. Finally, it is possible that DIS will soon be interfaced with robotic colony pickers and microtiter tray manipulators so as to increase the throughput and reliability of techniques requiring massively parallel screening of samples.

Visualization and processing of multidimensional data using prefiltering and sorting criteria

Patent number: 6834122

Abstract: Complex multidimensional datasets generated by digital imaging spectroscopy can be organized and analyzed by applying software and computer-based methods comprising sorting algorithms. Combinations of these algorithms to images and graphical data, allow pixels or features to be rapidly and efficiently classified into meaningful groups according to defined criteria. Multiple rounds of pixel or feature selection may be performed based on independent sorting criteria. In one embodiment sorting by spectral criteria (e.g., intensity at a given wavelength) is combined with sorting by temporal criteria (e.g., absorbance at a given time) to identify microcolonies of recombinant organisms harboring mutated genes encoding enzymes having desirable kinetic attributes and substrate specificity. Restriction of the set of pixels analyzed in a subsequent sort based on criteria applied in an earlier sort ("sort and lock" analyses) minimize computational and storage resources.

Type: Grant

Filed: January 22, 2001

Date of Patent: December 21, 2004

Assignee: Kairos Scientific, Inc.

Inventors: Mary M. Yang, Edward J. Bylina, William J. Coleman, Michael R. Dilworth, Steven J. Robles, Douglas C. Youvan